AFFDL-TR-78-66

TEST AND EVALUATION OF HALON 1301 AND NITROGEN INERTING AGAINST 23MM HEI PROJECTILES

CHARLES L. ANDERSON

MAY 1978

TECHNICAL REPORT AFFDL-TR-78-66
Final Report for Period 1 October 1976 – 28 February 1977

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

This technical report has been reviewed and is approved for publication.

CHARLES L. ANDERSON
Project Engineer

GEORGE R. HENNIG, Lt Col, USAF
Chief, Survivability/Vulnerability Branch
Vehicle Equipment Division

FOR THE COMMANDER

AMBROSE B. NUTT, Director
Vehicle Equipment Division
Air Force Flight Dynamics Laboratory

AIR FORCE/56780/7 July 1978 — 200

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AFFDL-TR-78-66	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Test and Evaluation of Halon 1301 and Nitrogen Inerting Against 23mm HEI Projectiles	5. TYPE OF REPORT & PERIOD COVERED 1 Oct 1976 - 28 Feb 1977
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Charles L. Anderson	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Flight Dynamics Laboratory Vehicle Equipment Division Survivability/Vulnerability Branch Wright-Patterson AFB, OH 45433	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62201F-43630130
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Flight Dynamics Laboratory Vehicle Equipment Division Survivability/Vulnerability Br, WPAFB, OH 45433	12. REPORT DATE May 1978
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government agencies only; test and evaluation; statement applied December 1977. Other requests for this document must be referred to Air Force Flight Dynamics Laboratory, AFFDL/FES, Wright-Patterson Air Force Base, OH 45433.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Unlimited

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fuel System
Vulnerability
Survivability
23mm HEI
Halon 1301 Inerting
Nitrogen Inerting
JP-4
Fuel Tank Protection

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Wright-Patterson AFB, OH
Test and Evaluation of Halon 1301 and Nitrogen Inerting Against 23mm HEI Projectiles, by Charles L. Anderson, Survivability/Vulnerability Branch, Vehicle Equipment Division, Air Force Flight Dynamics Laboratory, May 1978, (Report No. AFFDL-TR-78-66, publication unclassified)

The report presents the test results of an evaluation of Halon 1301 (CF_3Br) and nitrogen as fuel tank inertants. The inertants are compared to

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

internal foam and are evaluated under near worst case conditions. The 23mm HEI projectile is the primary threat investigated although the 23mm API projectile and high velocity fragments were also tested. JP-4 fuel was used to obtain worst case fuel/oxygen mixtures. The report contains information on test setup, results, conclusions, and the fuel/oxygen ratio measurement and control technique. Significant data is included on the explosion overpressures versus inertant concentrations.

FOREWORD

The effort described herein was performed by the Survivability/ Vulnerability Branch, Vehicle Equipment Division of the Air Force Flight Dynamics Laboratory. This effort was performed to answer questions concerning the performance of Halon 1301 and nitrogen inerting against primarily the 23mm HEI projectile threat.

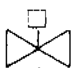
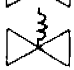
This program was performed for and funded by the Joint Technical Coordinating Group for Aircraft Survivability and the AF Flight Dynamics Laboratory. The program was performed under AFFDL Project Number 4363, Task 436301, Work Unit 43630130 and also JTCG/AS Project Number TF-6-17. The efforts described in this report were performed during the period of 1 October 1976 to 30 February 1977.

The author gratefully acknowledges the assistance of Lt Clarck Abelard for his efforts as Test Engineer, Mr. C. Harris for his work in gas sample analysis, and the Air Force Aero Propulsion Laboratory for providing the basic test specimen.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

NOMENCLATURE

AFFDL	Air Force Flight Dynamics Laboratory
API	armor piercing incendiary
HEI	high explosive incendiary
kPa	killo-pascals (1. psi = 6.895 kPa)
TWS	tank wall simulator
	manual valve
	solenoid valve
	gravity check valve
	poppet check valve
CF_3Br	Bromotrifluoromethane
Halon 1301	Bromotrifluoromethane
Sec	seconds
msec	milliseconds
min	minutes

SECTION I

INTRODUCTION

Due to the interest in and potential use of nitrogen and Halon 1301 as fuel tank inerting systems, this program was performed to provide data on the performance of these two protection concepts against the Soviet 23mm HEI projectile. Currently, the General Dynamics' F-16 incorporates a Halon 1301 fuel tank inerting system and other aircraft are considering using either Halon 1301 or nitrogen protection concepts.

The objective of this program was to compare the effectiveness of nitrogen, Halon 1301 (CF_3Br, Bromotrifluoromethane), and foam (Military Specification MIL-B-8354A) in the prevention of fuel/oxygen explosions in the ullage of aircraft fuel tankage as a result of ballistic impact. The maximum combustion overpressure in the tank after projectile impact was used as a measure of performance.

The type of threats included HEI, API, and warhead fragments with major emphasis being placed on the Soviet 23mm HEI. The test program was oriented around a tank wall simulator and evaluated the three protection concepts under (worst case) conditions (optimum for combustion fuel/oxygen ratio and minimum venting).

The prevention of explosions in the fuel tank ullage (the volume above the fuel level which contains air and fuel vapors) of combat aircraft is of major importance in reducing aircraft vulnerability. The polyester urethane reticulated foams were introduced in the late 1960's and represented a significant contribution to the survivability of any combat aircraft using this material. The primary drawback from using internal foam is its weight and fuel displacement/retention penalties. The use of nitrogen and Halon 1301 inerting, in general, both represent lighter weight inerting systems for most aircraft.

Present state-of-the-art nitrogen inerting systems store nitrogen onboard the aircraft in the liquid (cryogenic) state which leads to the logistical problems of storing and replenishing the cryogenic materials. On board nitrogen generation equipment is presently under advanced development by the Air Force. Successful development of such a system will make nitrogen inerting quite attractive, especially for larger aircraft.

Current system design for Halon 1301 inerting involves on board storage of the Halon in pressurized containers and subsequent dispersion in the fuel tanks prior to entering combat. With the protection time cut to a minimum, the total system weight is also kept to a minimum. Halon 1301 can also be stored indefinitely in pressurized containers making it more attractive than a cryogenic material from a logistic's viewpoint.

Due to the successful use of internal foam in Southeast Asia and the fact that the internal foam represents a totally passive system, the internal foam represents the most attractive type of protection concept from a purely survivability viewpoint. However, tradeoffs made by the aircraft designers to maximize mission effectiveness indicate that the lighter weight protection concepts are very attractive to the aircraft designer.

SECTION II

TEST APPROACH

1. TEST THEORY AND BACKGROUND

From references 1, 2, 3, 4, 6, 11, and 13, it was evident that the effectiveness (i.e., ability to prevent fuel tank explosions) of an oxygen dilution (i.e., nitrogen) and a chemical extinguishing (i.e., Halon 1301) protection concept are dependent upon the size and intensity of the ignition source, the volume of the tank, the amount of venting (size of hole in the fuel tank), and the amount of inertant. The different ignition sources to consider, range from a small spark, to a large high explosive incendiary (HEI) projectile. In between these two extremes are the armor piercing incendiary (API) projectile and simulated missile warhead fragments consisting of many sizes, shapes, and weights. The spark ignition source is not, in general, a combat hazard to the aircraft fuel tanks but can be a safety hazard. A static electricity discharge during fueling or a lightning strike are two safety hazards. The spark ignition source has been used in several tests due to its repeatability and simplicity. For all practical purposes, the spark ignition source can be considered a point ignition source.

The size of the ignition source is a critical parameter in determining the overall reaction in the fuel tank ullage. With a point ignition source, the flame front initiates from a point and radiates spherically throughout the fuel tank. For conditions encountered in an aircraft fuel tank, a fuel/air explosion will be a deflagration (subsonic flame front speed) and not a detonation (supersonic flame front speed). The pressure rise time of the explosion is directly related to the flame front speed and the dimensions of the tank. When heat transfer and especially venting are considered, the rise time becomes extremely important. During the finite time that is required for an explosion to occur (i.e., time from beginning to end of combustion), venting and heat transfer combine to reduce the peak combustion pressure. Shorter rise times of the combustion pressure leave less time for venting and heat transfer to reduce the peak combustion pressure.

The 23mm API projectile used in this test program contained 4.5 grams of incendiary filler composed of aluminum, TNT, barium nitrate, and wax. The 23mm HEI projectile used in this test program contained 13.4 grams of explosive filler composed of aluminum, RDX, and binder. The HEI projectile produces a larger and more intense ignition source than the API projectile.

For nitrogen inerting, the levels of nitrogen concentration are referred to in terms of oxygen concentration since nitrogen inerting is in effect an oxygen dilution type of inerting technique. Oxygen concentrations are generally referred to as percent by volume (20.9% for normal air). Results presented in references 1 and 3 using API and spark ignition sources indicated that a reduction of O_2 concentration to approximately 10% or less by volume was adequate to assure complete inerting.

Previous test results, from reference 6, using Halon 1301 against small ignition sources such as spark and small caliber API indicated that Halon concentrations of approximately 6% and 10% by volume, respectively, would be effective. These data indicated that a lower concentration was required for spark ignition sources than for API projectiles. This indicated that the performance of Halon 1301 is strongly dependent on ignition source size and intensity. Halon 1301 has been used as a fire extinguisher for several years in areas such as aircraft engine nacelles, buildings, and enclosures where personnel would be present. Halon 1301 is considered to be one of the most effective and safest fire extinguishers available due to its low required concentrations. It should be fully understood that for a fuel tank inerting application, the Halon 1301, technically, is not a fire extinguishing material dispersed after a fire is initiated. Instead, the Halon 1301 must be thoroughly dispersed throughout the fuel tank prior to introducing the ignition source (i.e., prior to entering combat).

The specific mechanism by which CF_3Br inhibits combustion is not fully understood. However, reference 12 suggests that CF_3Br extinguishes by a chemical action. The halogen compound is believed to react with the transient combustion products (free radicals) which are responsible for rapid and violent flame propagation. This reaction terminates the chain reaction involved in combustion and thereby stops the flame propagation. Due to the scant data available, the actual performance of the Halon 1301 with various large ignition sources, such as 23mm HEI, was an unknown.

As mentioned earlier, venting is probably one of the most significant factors affecting the overpressures encountered in fuel tank explosion. It should be understood that an effective fuel tank inerting concept need only prevent fuel tank overpressures from reaching levels where significant structural damage will occur. Halon 1301 and nitrogen protection concepts can be considered effective at concentrations that still allow a small overpressure.

Flame front velocity will decrease (pressure rise times will increase) as the inertant concentrations increase or fuel/oxygen ratios vary from values optimum for combustion. From the beginning of a projectile initiated explosion, venting (from entrance and exit holes) and heat transfer (to surrounding structure) combine to lower the peak overpressure. The amount of venting present in a fuel tank impacted by a 23mm HEI projectile varies widely depending upon impact obliquity, types of structure, etc. The absolute minimum amount of venting that could occur would involve only an entrance hole. Venting, from the entrance hole only, is probably rarely encountered in actual combat damage but would represent a worst case condition as far as venting is concerned. The venting condition used in this test program involved just the entrance hole. This also serves to eliminate venting as a variable which would be hard to control and measure. The test specimen selected was a heavy walled Tank Wall Simulator (TWS) which allowed a small aluminum impact plate to be mounted.

2. FUEL/O_2 RATIO MANAGEMENT CHECKOUT TEST

A considerable amount of discussion and thought went into the selection of a hydrocarbon fuel to produce the optimum for combustion fuel/oxygen ratio. It was felt that JP-4 fuel should be used in order for a high realism test to be performed. However, problems associated with performing a test with

JP-4 precluded its use with conventional test techniques such as those covered in reference 11. For this reason, an effort was made to devise a workable technique using JP-4 to produce the desired fuel/oxygen ratios.

A system was devised which allowed excellent control of the fuel/oxygen ratio without introducing liquid fuel into the TWS. This technique consists of circulating the ullage mixture from the TWS through a small container of liquid JP-4, where the ullage mixture picks up JP-4 vapors, and back to the TWS (closed loop system). The TWS also contained an internal fan to maintain a homogeneous mixture of the various gases present in the TWS. In operation, the fuel vapor generation system gradually increased the amount of fuel vapor in the TWS. The details of the system, and how each test was conducted, are discussed in Section III.

With this type of system, it was mandatory that some type of technique or instrument be devised which was capable of monitoring fuel/oxygen ratio or more preferably, the combustibility. The success of this test program was dependent on developing an entire test setup which could obtain and monitor a "worst" case fuel/oxygen ratio. The "bomb sample" technique was selected in this program due to its simplicity and its successful use in previous tests. The bomb sample system is discussed in detail in Section III.

The bomb sample system is basically a very simple one. The sampler is initially evacuated and then filled with a sample of the fuel/air mixture in the TWS. The mixture of air and JP-4 vapors is then ignited with a spark plug installed in the sampler. An attached pressure transducer provides a means of recording the ensuing pressure rise and peak pressure. The peak pressure is a direct measure of fuel/air mixture combustibility and is referred to as a "bomb sample pressure". It should be noted that a stoichiometric fuel/oxygen ratio is not desired in this case. The optimum for combustion fuel/air mixture occurs at a fuel/oxygen ratio on the slightly rich side of stoichiometric. As the fuel/oxygen ratio in the fuel tank increases, the bomb sample pressures will increase to a peak value and then decline. This peak bomb sample pressure corresponds to an optimum fuel/oxygen ratio.

A checkout of this technique was planned to solve any problems with the test setup, prove that the bomb sample system could effectively monitor ullage combustibility, and evaluate the adequacy of the test setup in producing repeatable controlled fuel/oxygen ratios. The checkout involved starting the circulation of the fuel tank gases through the liquid JP-4 (JP-4 bubbler tank) and then periodically obtaining bomb samples. The fuel/oxygen ratio was allowed to increase until the bomb sample pressures peaked out and showed a definite decline. In normal operation, no additional fuel vapor would be added to the TWS after reaching the optimum fuel/oxygen ratio, but during these checkout tests the fuel/air mixture was allowed to reach a rich condition in order to fully evaluate the test setup performance and repeatability.

3. BASELINE BLAST PRESSURE AND O_2 USAGE TEST

The detonation of a 23mm HEI in an enclosed structure such as a fuel tank ullage will result in an internal pressure due to the blast and release of gases. The HEI also has the potential of changing the chemical composition of the gases present in the tank.

The pressure encountered in the ullage of a fuel tank when a 23mm HEI projectile detonates is composed of several frequency components and can be divided into 3 areas: (1) the highly dynamic blast pressure (shock waves) which radiate from the detonation point, reflect off the fuel tank walls, and reverberate for several cycles; (2) the quasi-static overpressure resulting from the release of gas from the HEI detonation, which effectively cause a step increase in tank pressure and a slow decline as the gases are vented from the tank; (3) the quasi-static overpressures generated by the fuel and oxygen combustion. The term "quasi-static pressure" is used in this report to differentiate between the pressure that the walls of the TWS feel due to gas pressure and that due to the blast shock waves. Figure 1 depicts the three distinct frequency components as they would exist if they could be separated. It is important to obtain a good understanding of the projectile's contribution to tank overpressure so that the combustion overpressure can be differentiated from the blast pressures.

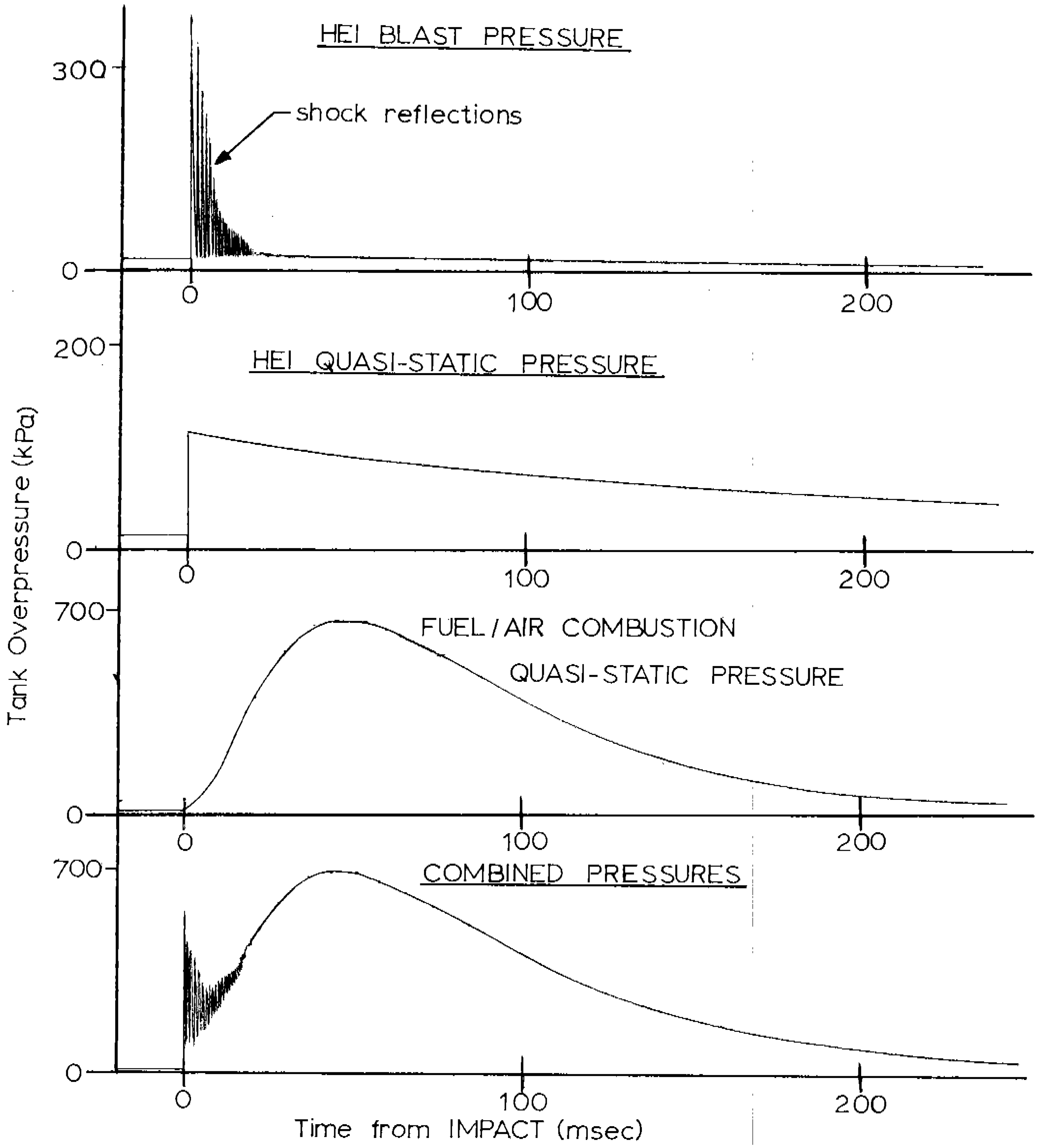


Figure 1. 23MM HEI/Combustion Pressure Breakdown

An analysis of the chemical reaction between the detonation products of a 23mm HEI and surrounding oxygen is presented in reference 14. The analysis indicates that the high explosive reaction does not require oxygen but that the detonation products will react with surrounding O_2 if it is available. Depending on the amount of O_2 present in a fuel tank ullage, the scavenging of O_2 by the detonation products could result in a partial self-inerting for an HEI projectile. The analysis presented in reference 14 predicts that detonation products from a single 23mm HEI could scavenge O_2 from up to 34.5 liters of air thus reducing the O_2 concentration in a 750 liter volume from an initial 20.9% by volume to 19.9% by volume. The baseline O_2 usage test evaluated this theory by measuring O_2 concentrations after HEI detonations in an air filled TWS. This is discussed in detail in Section III.

4. IGNITION SOURCE MAGNITUDE TEST

As mentioned earlier, the magnitude and intensity of an ignition source are believed to have an effect on the performance of both nitrogen and Halon 1301 inerting. A test series designed to show the effects of various ignition sources was conducted by choosing an inerting level which was considered marginal and testing inerting levels against the different ignition sources (spark, API, fragments, and HEI). The peak combustion overpressure and the pressure rise time were used as a basis of comparing the effects of ignition source size.

5. HALON 1301 AND NITROGEN INERTING TEST

This series of inerting tests yielded the primary data for the entire program. The system checkout, blast pressure, self-inert, and ignition source magnitude tests were preliminary tests and only laid the foundation for these primary inerting tests. As mentioned earlier, the measure of performance for both inerting techniques was combustion overpressure. The variables in this test series included percent by volume of Halon 1301 and nitrogen. The 23mm HEI was used for all tests in this series. The results are presented in a graph of peak combustion overpressure versus inertant concentration. The overall simplicity of this test makes it easy to understand and apply the results.

6. INTERNAL FOAM TEST

The primary objective of this foam test series was to provide a standard to which the Halon 1301 and nitrogen data could be compared. Due to the unique test techniques applied in this test, it was decided to test a typical internal foam installation in order to provide a one-to-one comparison of foam to the Halon 1301 and nitrogen inerting tests. It has been shown in reference 11 that wet foam performs better than dry foam, but that the difference is not large. This series of foam tests were performed with dry foam to simplify the test setup knowing that the overpressure data would be slightly higher for the dry foam than for the fuel-wetted foam.

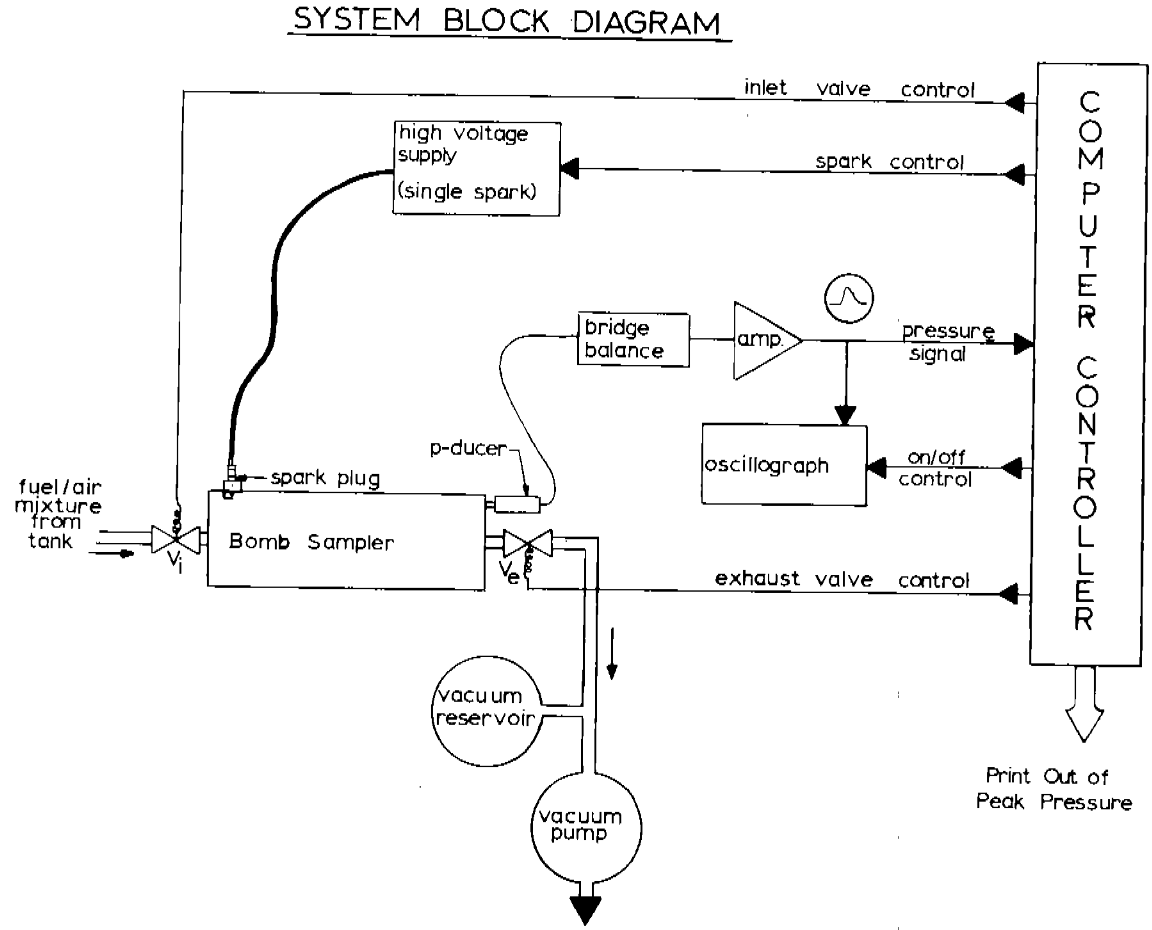
SECTION III

TEST SETUP/PROCEDURE

1. BOMB SAMPLE SYSTEM

The bomb sample system consisted of the following components: high pressure cylinder, spark plug, high voltage source, pressure transducer, associated solenoid valves, vacuum pump, oscillograph, and computer controller. The bomb sample system is an effective method of directly measuring the relative flammability of fuel and air mixtures. The system operated by trapping an uncontaminated sample of the fuel and air mixture from the fuel tank, igniting the mixture, and measuring the peak pressure of the contained explosion (referred to as the bomb sample pressure).

The high pressure cylinder was made of stainless steel and had a volume of approximately 262 milliliters. Two solenoid valves at both ends of the cylinder controlled the flow of gases in and out of the sampler. The outlet of the sampler was connected to a vacuum pump with a vacuum accumulator. The vacuum system was sized to maintain a constant vacuum of less than .1 kPa (.0145 psi) absolute. The spark plug was a standard automotive plug with a voltage source designed to fire a single high energy spark on command. The pressure transducer was a standard strain gage transducer capable of measuring absolute pressures to 700 kPa. The solenoid valves had approximately 1 cm ports to permit high flow rates in and out of the sampler. The oscillograph was used to record the analog trace of the pressure pulse after igniting the mixture within the sampler. This analog trace was used as a backup record for the computer and a qualitative check of system performance. The computer controlled the sequencing of all elements of bomb sample system and the rate at which samples were taken, analyzed the pressure pulse, and provided a printout of the actual peak pressure (bomb sample pressure) on a real time basis. The computer control of the bomb sample allowed the system to operate with a maximum speed of one sample every 7 seconds. Figure 2 depicts the bomb sample system and pressure history for one operation cycle. During a test, the bomb sample system was programmed to sample at regular intervals (generally 15 seconds) depending on the rate at which the fuel/oxygen ratio was increasing.



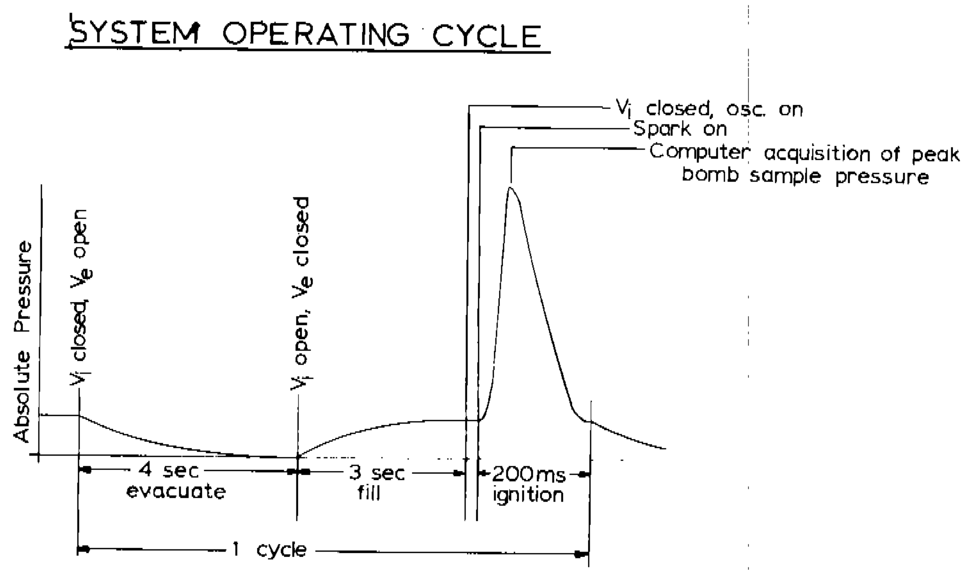


Figure 2. Bomb Sample System

The bomb sample pressure that the computer provides was plotted versus time in order to provide a trend of combustibility. This plot was used as a graphical aid in determining when an optimum fuel/air ratio was reached.

2. FUEL VAPOR GENERATION SYSTEM

The air, from the TWS, was first circulated (via a bellows pump) to the bubbler tank. The bubbler tank, which was a 30 liter container containing approximately 20 liters of JP-4, allowed the air to enter at the bottom through a fine mesh screen to produce a large number of bubbles. The air bubbles passing through the liquid JP-4 accumulated JP-4 vapors before leaving top of the bubbler tank. The air and JP-4 vapor mixture was then returned to the TWS (closing the loop) where it was mixed with aid of a fan. The bubbler tank itself was kept at approximately 20-25° C. The TWS and all other plumbing was kept at a higher temperature (38° C) in order to avoid any condensation of fuel vapors. When the proper fuel/oxygen ratio was reached, the fuel vapor generation system was isolated from the TWS via two remote control solenoid valves. This prevented any further fuel vapor from entering the TWS and altering the fuel oxygen ratio.

3. INSTRUMENTATION

a. Pressure Measurement

The combustion overpressures inside the TWS were measured primarily with standard strain gage transducers having a frequency response from 0 to 1000 Hz. This pressure measurement was extremely important and received much attention during the test program. The piezioelectric type of pressure transducer was also used since it was not known at the beginning of testing which type of transducer was best suited for the data of interest. The piezioelectric transducers proved to be less accurate due to their high sensitivity to temperature and lack of response to low frequency pressures. As will be discussed in the Results Section, the blast pressures were not difficult to distinguish from the combustion overpressures. The pressure transducers used were vibration isolated from the main fuel tank by a short vinyl tube. There were two transducers used for redundancy and data from both were recorded on magnetic tape for playback at a later time. The

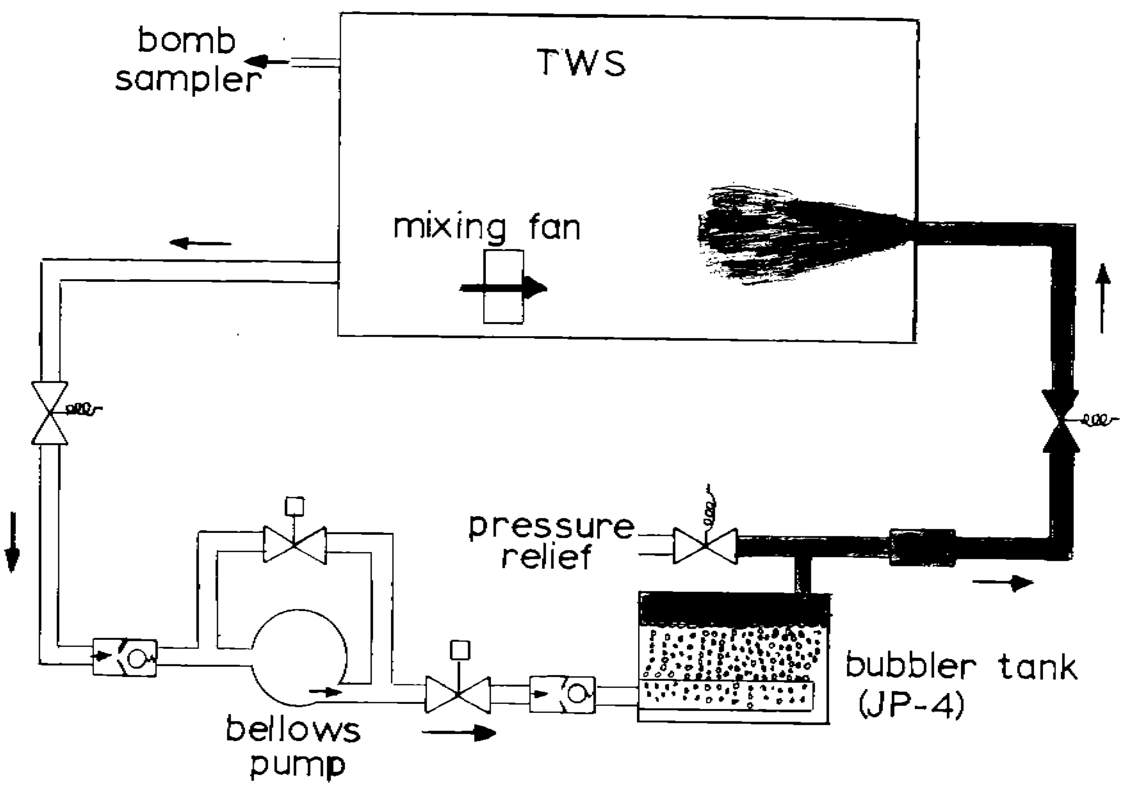


Figure 3. Fuel Vapor Generation System

recorded pressure data was played back on an oscillographic recorder. Further data reduction was provided for by a programmable calculator, digitizer, and plotter. Using the digitizer and plotter, a reproducible plot with axes in engineering units was provided. The overpressure histories presented in this report were generated in this manner.

A low range, absolute pressure, transducer was also used to monitor and control the TWS pressure during the mixing of the inertants. This transducer had a range of 170 kPa absolute and was isolated from the tank by a solenoid valve before projectile impact to prevent damage to the transducer from overpressures. The TWS pressure was visually displayed in real time on a digital display. The real time display was required in order to accurately control the mixing of the inertants in the proper proportions.

b. Temperature Measurement

The ullage temperature inside the TWS and the liquid fuel temperature in the bubbler tank were measured using thermocouples and visually displayed on a digital temperature display. These were monitored constantly to ensure proper temperature regulation.

c. Oxygen Measurement

The O_2 concentration (% by volume) in the TWS was measured in certain cases after the HEI detonation. This was done by passing a continuous sample of gas from the TWS through an oxygen analyzer. The operating principal of the analyzer was based upon changes in oxygen partial pressure causing changes in the electrical conductivity of a solid electrolyte.

4. RANGE/SPECIMEN SETUP

The test program was conducted on Range 2 of the Aircraft Survivability Research Facility. This facility is an outdoor gun range designed for horizontal gunfire. A photograph of the range area is shown in Figure 4. The weapon was mounted approximately ten meters from the target and fired horizontally. The TWS was installed in Range 2 along with all associated

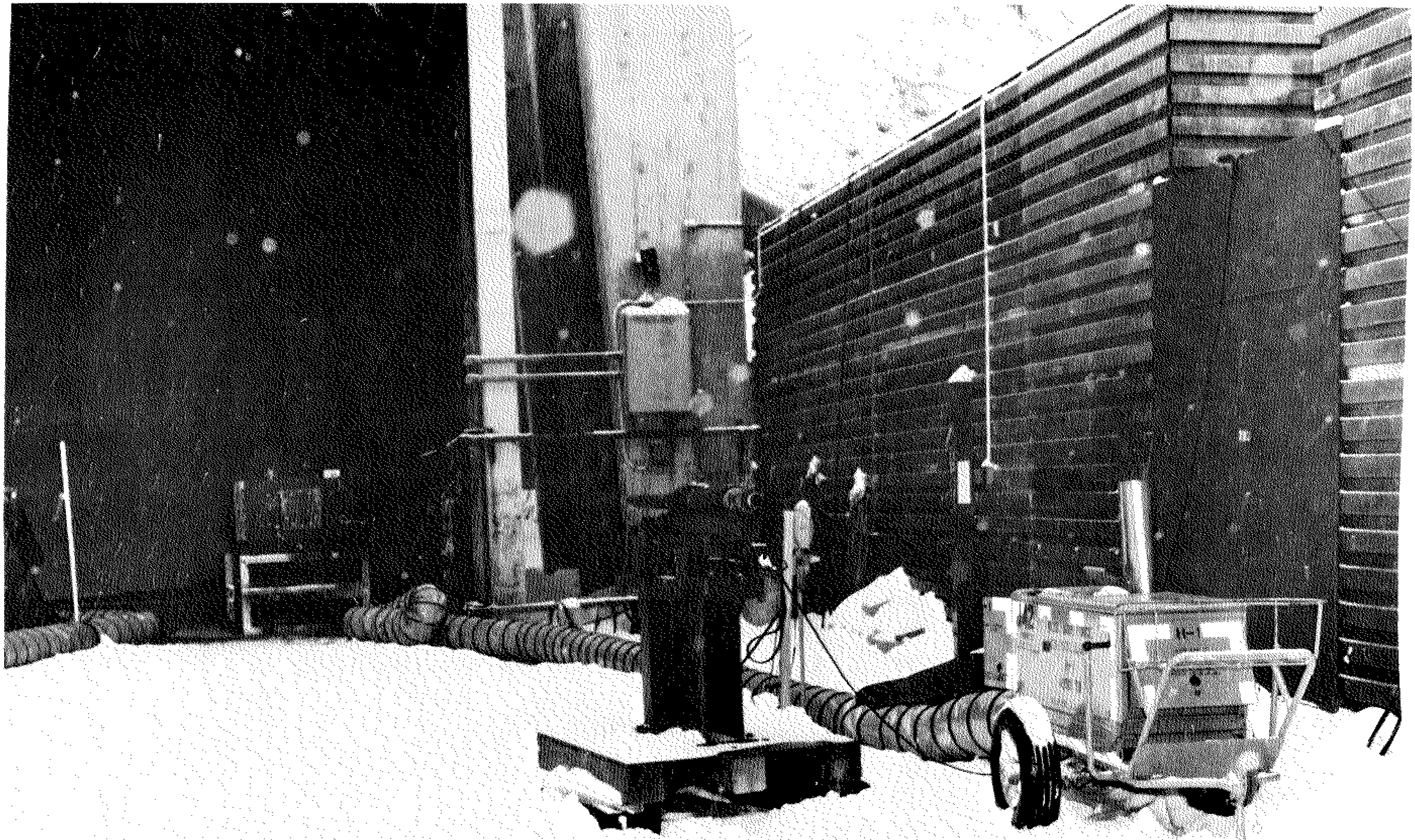


Figure 4. Test Setup and Range Area

equipment such as vacuum pump, circulation pump, bubbler tank, etc. Due to the low winter temperatures encountered, the heating setup was required to maintain the required specimen temperature. A schematic of the specimen and associated plumbing is shown in Figure 5 with photographs of the actual specimen shown in Figures 6 and 7.

5. INERTANT MIXING

The method used in this test program to obtain the desired concentrations of Halon 1301 and O_2 (for N_2 inerting), involved the use of the perfect gas laws and Dalton's Law of Partial Pressures. Dalton's Law of Partial Pressures states that in any gas mixture the total pressure is equal to the sum of the pressures which each gas would exert where it alone present in the volume occupied by the mixture; i.e., the total pressure is equal to the sum of the partial pressures of the individual gases. From these two basic laws, the following relations hold true:

$$\%\text{ by Volume of } O_2 = \frac{\text{Partial Pressure of } O_2}{\text{Total Pressure}} \times 100 = \frac{P_{O_2}}{P} \times 100 \qquad (1)$$

$$\%\text{ by Volume of } CF_3Br = \frac{\text{Partial Pressure of } CF_3Br}{\text{Total Pressure}} \times 100 = \frac{P_{CF_3Br}}{P} \times 100 \qquad (2)$$

where P = total pressure

P_{O_2} = partial pressure of O_2

P_{CF_3Br} = partial pressure of CF_3Br.

The total calculation used for mixing Halon 1301 was less complicated than that used for nitrogen since the Halon 1301 was not initially present in the gas mixture in the TWS. Equation 2 yielded the relationship used when adding Halon 1301 by substituting the total pressure at test time (108. kPa absolute):

$$\%\text{ by Volume of } CF_3Br = \frac{P_{CF_3Br}}{108.} \times 100 \qquad (3)$$

which simplifies to:

$$\text{Desired } P_{CF_3Br} = \frac{108. \times (\text{Desired \% by Volume of } CF_3Br)}{100} \qquad (4)$$

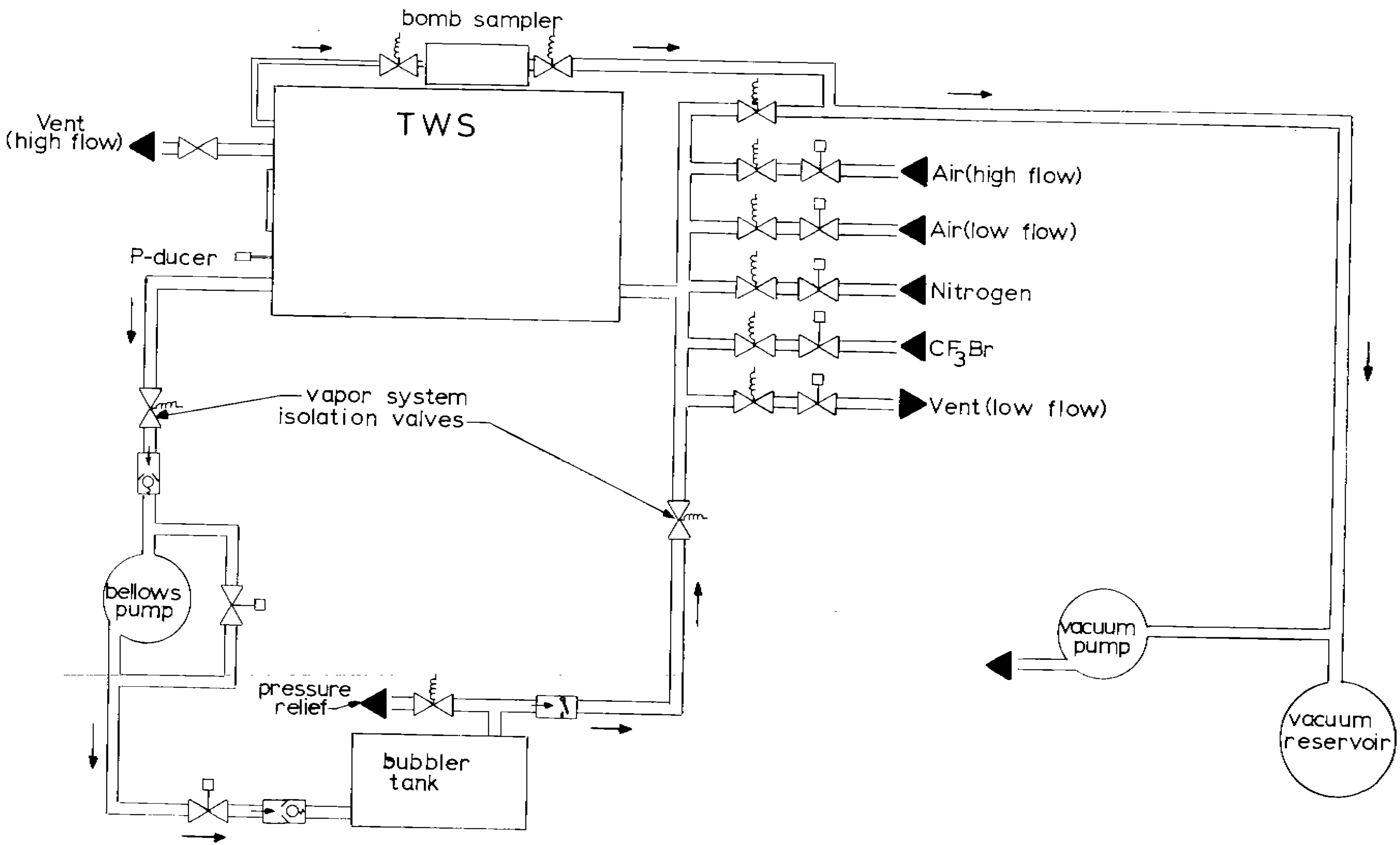


Figure 5. Specimen/Plumbing Schematic

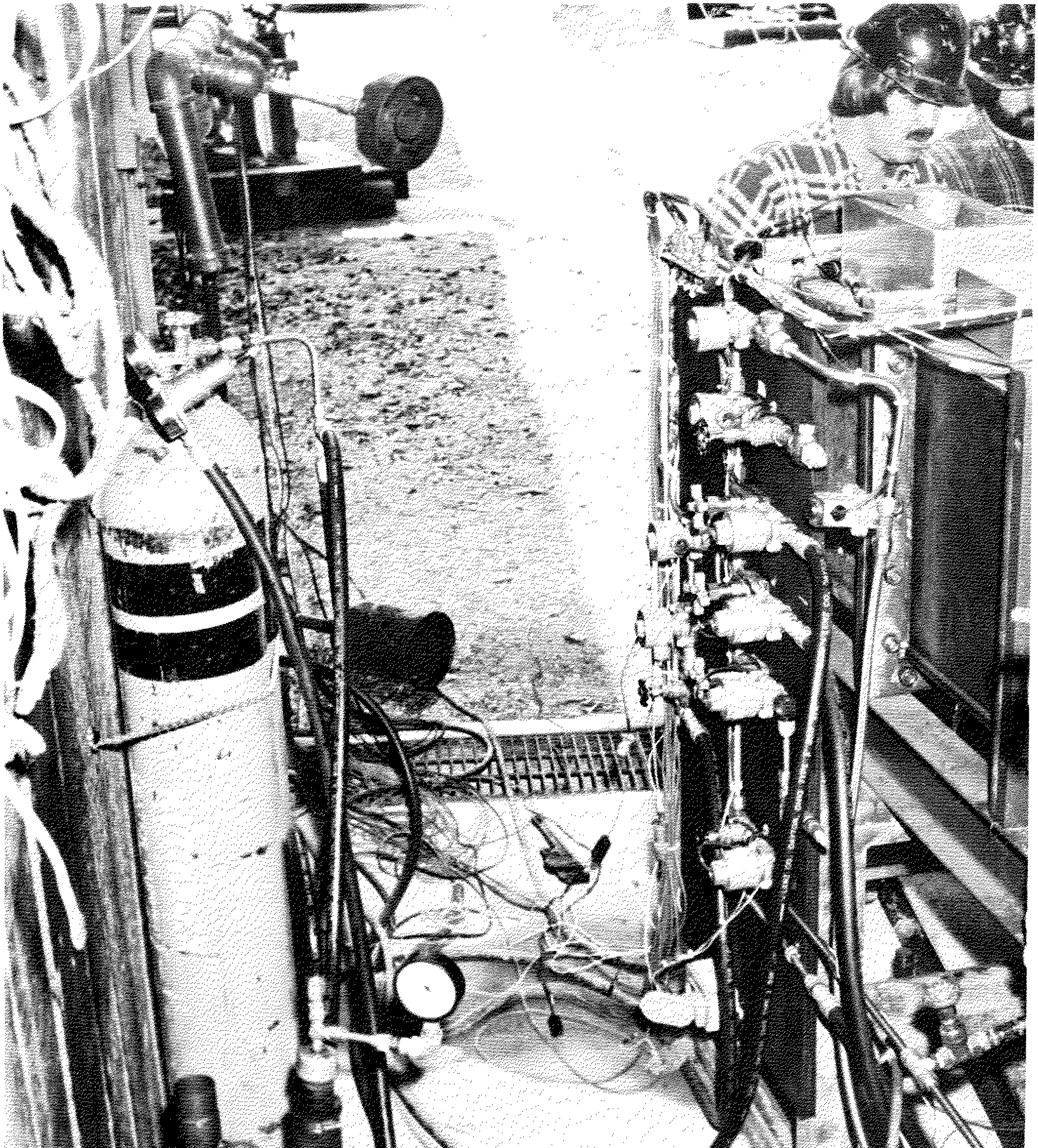


Figure 6. Test Specimen

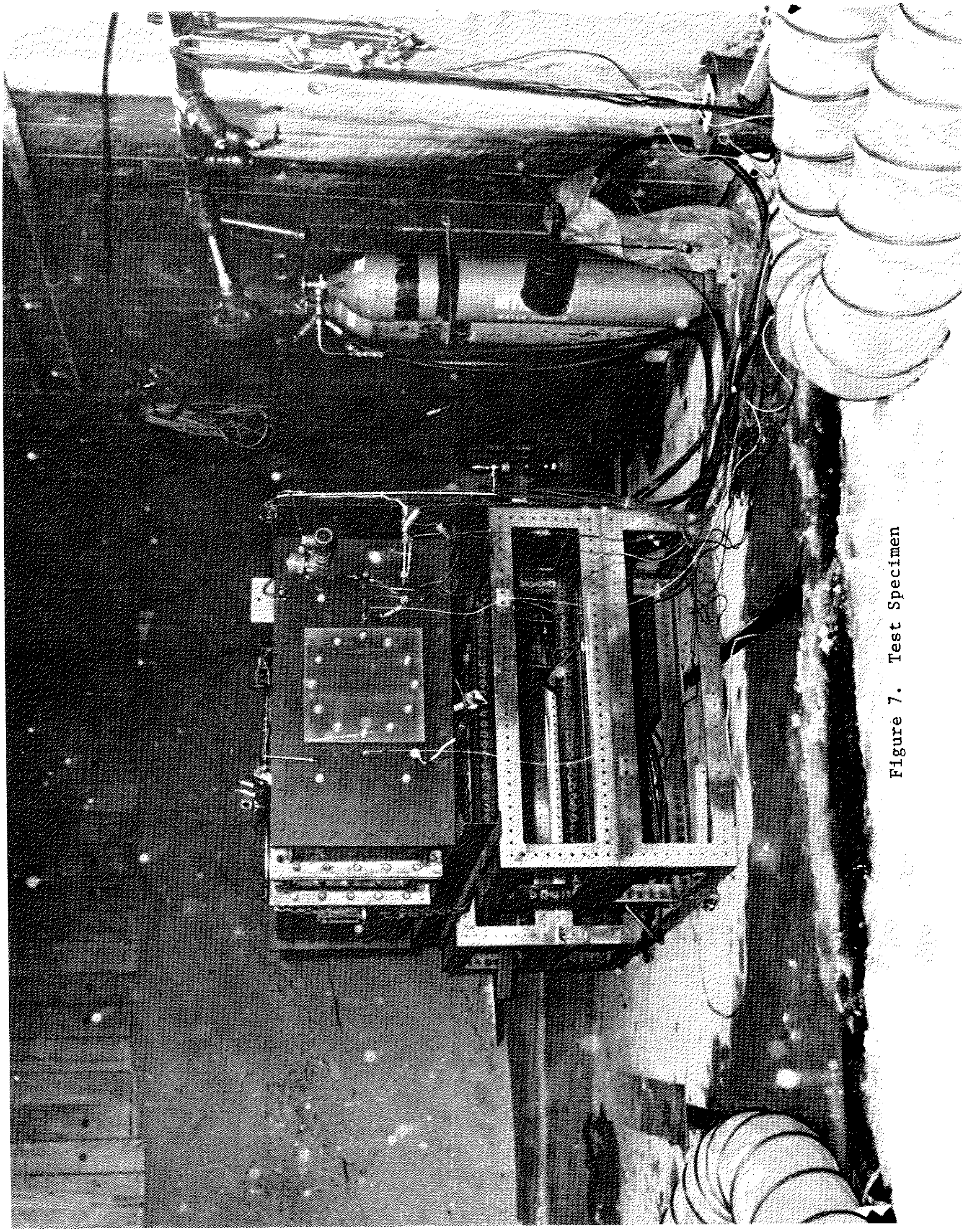


Figure 7. Test Specimen

Equation 4 yields a partial pressure of Halon 1301 for any desired percentage by volume of Halon 1301. The partial pressure of Halon 1301 was obtained in the TWS by reducing the absolute pressure in the TWS, from the initial 108. kPa, by an amount equal to the partial pressure of Halon 1301 specified in equation 4 . The Halon 1301 was then added to the TWS until the absolute pressure was returned to 108. kPa.

The calculation used when mixing N_2 was more involved since N_2 and O_2 were initially present in the air that was in the TWS. Since levels of nitrogen inerting are expressed in terms of O_2 concentrations, the percentage of O_2 present initially had to be known to a reasonable level of accuracy. The O_2 concentration in air is approximately 20.9% by volume. However, in the TWS just prior to the addition of the nitrogen, there are also JP-4 fuel vapors at an estimated concentration of 2.5% by volume according to reference 1. Therefore, with the fuel vapors present, the O_2 concentration was reduced to approximately 20.4% by volume.

Equation 1 was used to derive the following relationships involved in mixing the nitrogen to obtain the desired O_2 concentrations. Prior to N_2 being added to the TWS, the initial partial pressure of O_2 is given as:

$$\text{Initial } P_{O_2} = \frac{(\text{Initial \% by Volume of } O_2) \times P}{100} \tag{5}$$

where P = 108. kPa

The desired inerting level (i.e., % by Volume of O_2) was related to the desired partial pressure of O_2 using the following relationship:

$$\text{Desired } P_{O_2} = \frac{(\text{Desired \% by Volume of } O_2) \times P}{100} \tag{6}$$

Substituting 108. kPa for P yields:

$$\text{Desired } P_{O_2} = \frac{(\text{Desired \% by Volume of } O_2) \times 108.}{100} \tag{7}$$

By reducing the total pressure of the homogeneous gas mixture in the TWS, the partial pressure of any individual gas can be reduced proportionally. Therefore, the first step in mixing the N_2 in TWS was to reduce the total pressure, thereby reducing the initial partial pressure of O_2 given by equation 5 , to the desired partial pressure given by equation 7 . At this point, the percentage by Volume of O_2 still remained at 20.4%.

By rearranging equation 1 and substituting 20.4% for % by Volume of O_2 and equation 7 for P_{O_2} the following equations can be obtained defining the value that the total pressure in the TWS was reduced to:

$$\text{Reduced P} = \frac{\text{Desired } P_{O_2}}{20.4} \times 100 \tag{8}$$

Further substitutions from equation 7 yields:

$$\text{Reduced P} = \frac{(\text{Desired \% by Volume of } O_2)}{20.4} \times 108. \times 100 \tag{9}$$

Once the total pressure in the TWS was reduced to the value given by equation 9 , the total pressure was increased to 108. kPa by adding N_2 to the TWS. The TWS then contained the desired concentration of O_2 at the desired test conditions.

SECTION IV

TEST RESULTS

1. PRELIMINARY CHECKOUT TEST RESULTS

The preliminary checkout tests were devoted to a total checkout of the test setup and its ability to produce optimum combustible fuel/oxygen ratios in a reliable and repeatable fashion. Many tests were conducted which involved a general shakedown of the equipment such as the circulation pumps, control systems, etc.

Once the test setup was debugged, several tests were conducted allowing the fuel vapor generation system to run continuously as bomb sample pressures were taken. These tests resulted in a plot of bomb sample pressures versus time for each test. Figure 8 is an example of a typical test. Note that, for the first several minutes after the fuel vapor began to accumulate, there was no data given on the plots. This was because there was no reaction from the bomb sampler until the fuel/oxygen ratio reached the lower explosive limit (LEL). The first data points indicated that the fuel/oxygen ratio was at or about the LEL in the TWS. After the first bomb sample pressure was registered, successive bomb sample pressures showed a gradual increase until they finally peaked out. Each bomb sample pressure was printed out by the computer at 15 second intervals and immediately hand plotted to give a graphical indication of relative combustibility. The value at which this plot of bomb sample pressures versus time would peak out at (peak bomb sample pressure) varied slightly between tests. It should be noted that the peaking out of the bomb sample pressures was used as an indication of reaching an optimum combustible mixture. During a normal inerting test, after an optimum combustible mixture was reached, the fuel vapor generation system was shut down and isolated from the TWS to preserve the desired mixture. However, during these checkout tests, the bomb sample pressures were allowed to peak out and then continue in a downward trend as the mixture became over rich. The mixture was allowed to become over rich only during the checkout tests to determine the repeatability and shape of the plot as presented in Figure 8.

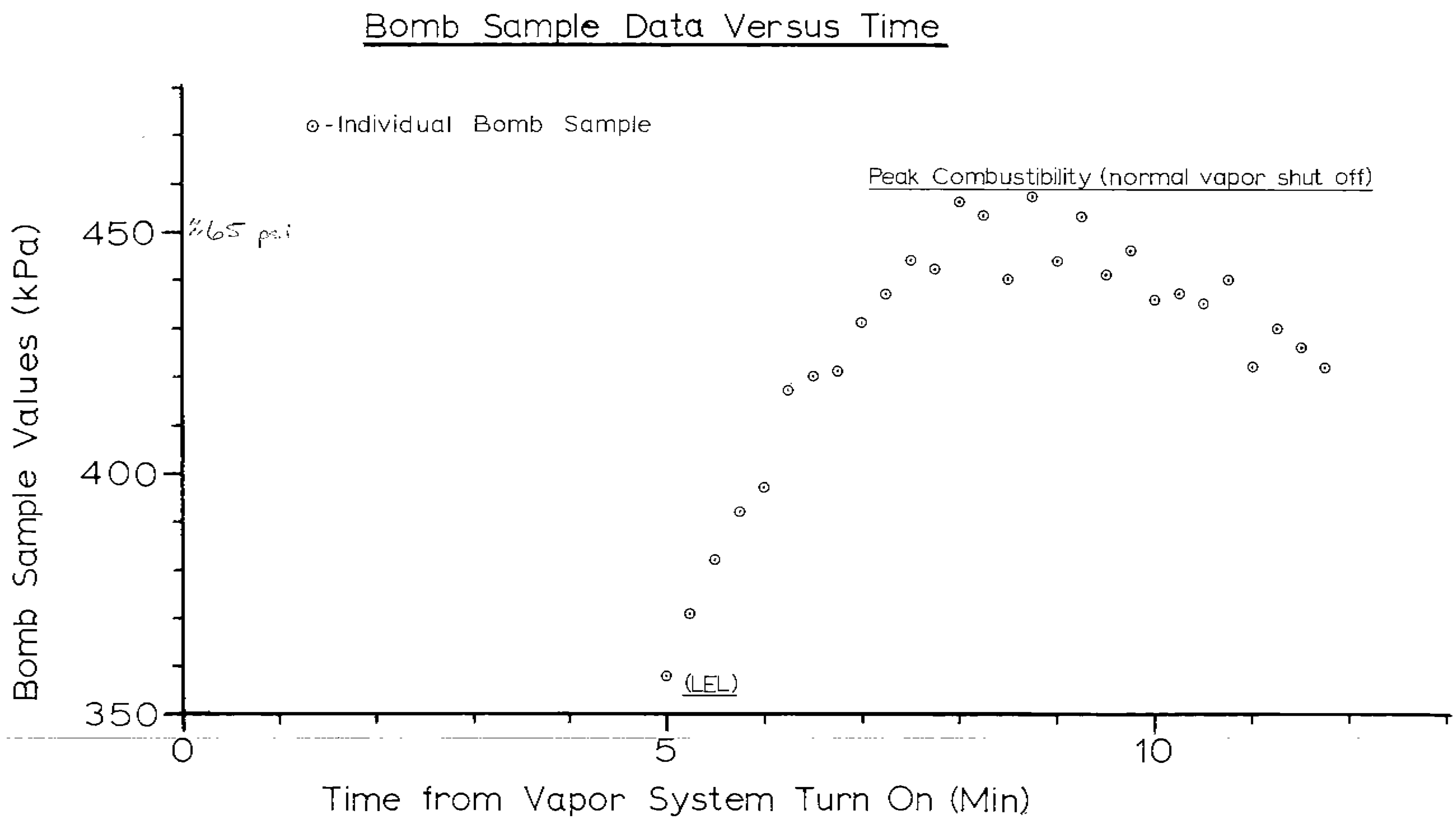


Figure 8. Bomb Sample Data Versus Time

2. BASELINE BLAST PRESSURE AND O_2 USAGE TEST RESULTS

This series of tests involved firing 23mm HEI projectiles into the TWS containing air only (i.e., no fuel vapors). There were a total of eight tests performed under the same conditions. Figure 9 shows a typical pressure-time history plot from this test series. The data in Figure 9 showed several pressure spikes riding on an abrupt pressure increase which averaged approximately 100 kPa. This data agreed very well with what was expected. The pressure spikes are shock waves reverberating inside the TWS and gradually decrease as they are dampened. The data from this test series, as shown in Figure 9, indicated that the shock waves were nearly dissipated in approximately 20 milliseconds. This data indicated that the pressure spikes would be nearly dissipated prior to the peak in combustion overpressure, thereby simplifying the data reduction to determine peak combustion overpressure.

Each of the tests performed in this test series also yielded data on the amount of O_2 depleted after the 23mm HEI detonation. Figure 10 shows the analyzer readings versus time for a typical test.

3. IGNITION SOURCE MAGNITUDE TEST RESULTS

For this series of tests, an optimum combustible mixture was obtained and then the TWS was inerted at the desired levels following the procedure described in Section III. All of the inerting tests in this series were performed at a pressure of 108. (15.7 psi) kPa absolute. The object of the ignition source magnitude tests was to perform the tests at inerting concentrations which were considered marginal so that the effects of ignition source size would be more pronounced. From the data presented in references 1, 2, 3, 4, 5, 6, and 13 it was decided to perform the tests in this series using 8% by volume Halon 1301 and 14% by volume O_2 (N_2 inerting).

The results of the Halon 1301 tests are presented in Table 1. It was excepted that all of the various ignition sources tested would produce some combustion reaction, with the smaller ignition sources producing a lower combustion overpressure and a slower risetime. However, at 8% Halon, the effects of ignition source size and intensity was so pronounced with the Halon 1301 that there was no measureable combustion overpressure

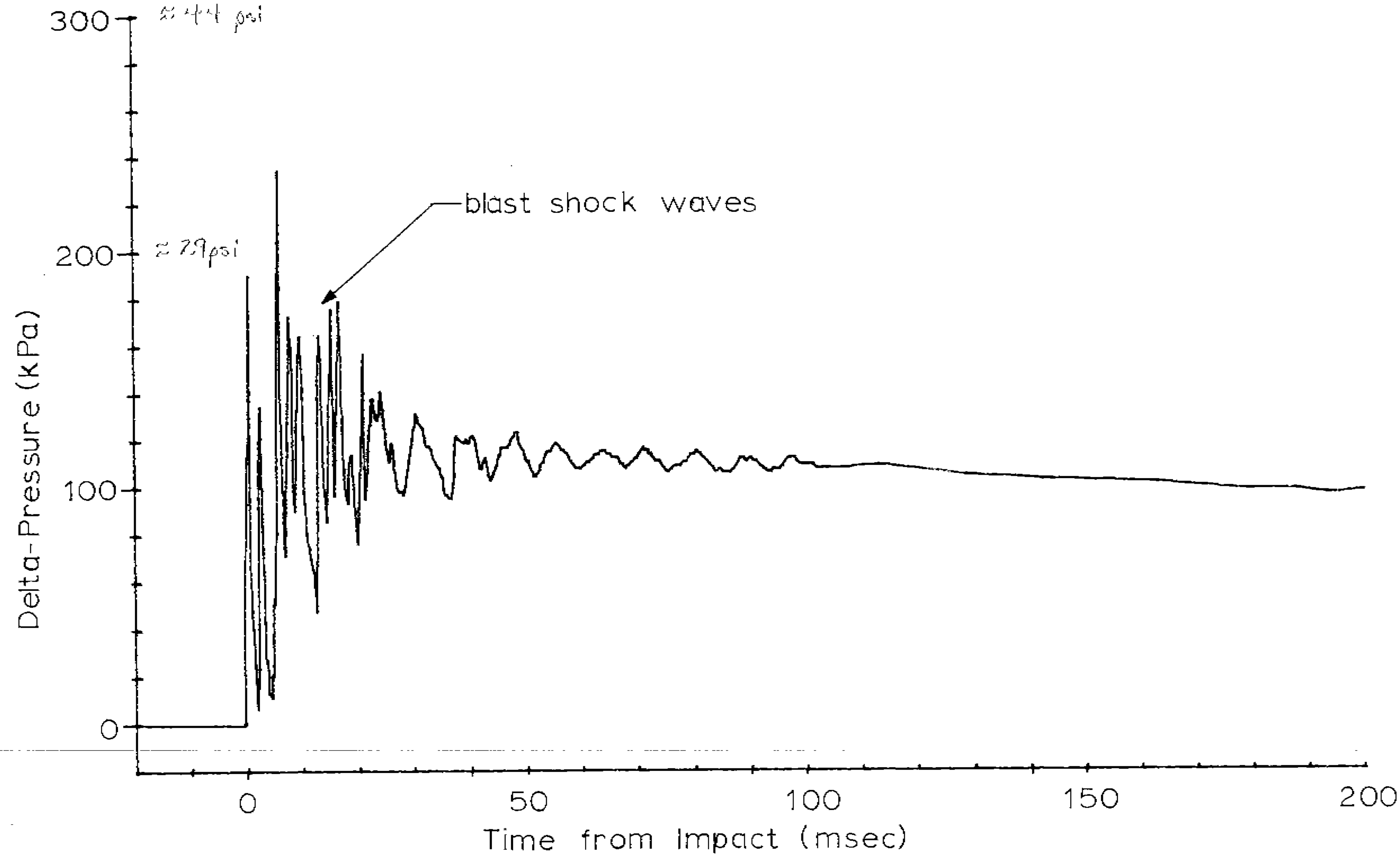


Figure 9. Baseline 23MM HEI Induced Overpressures

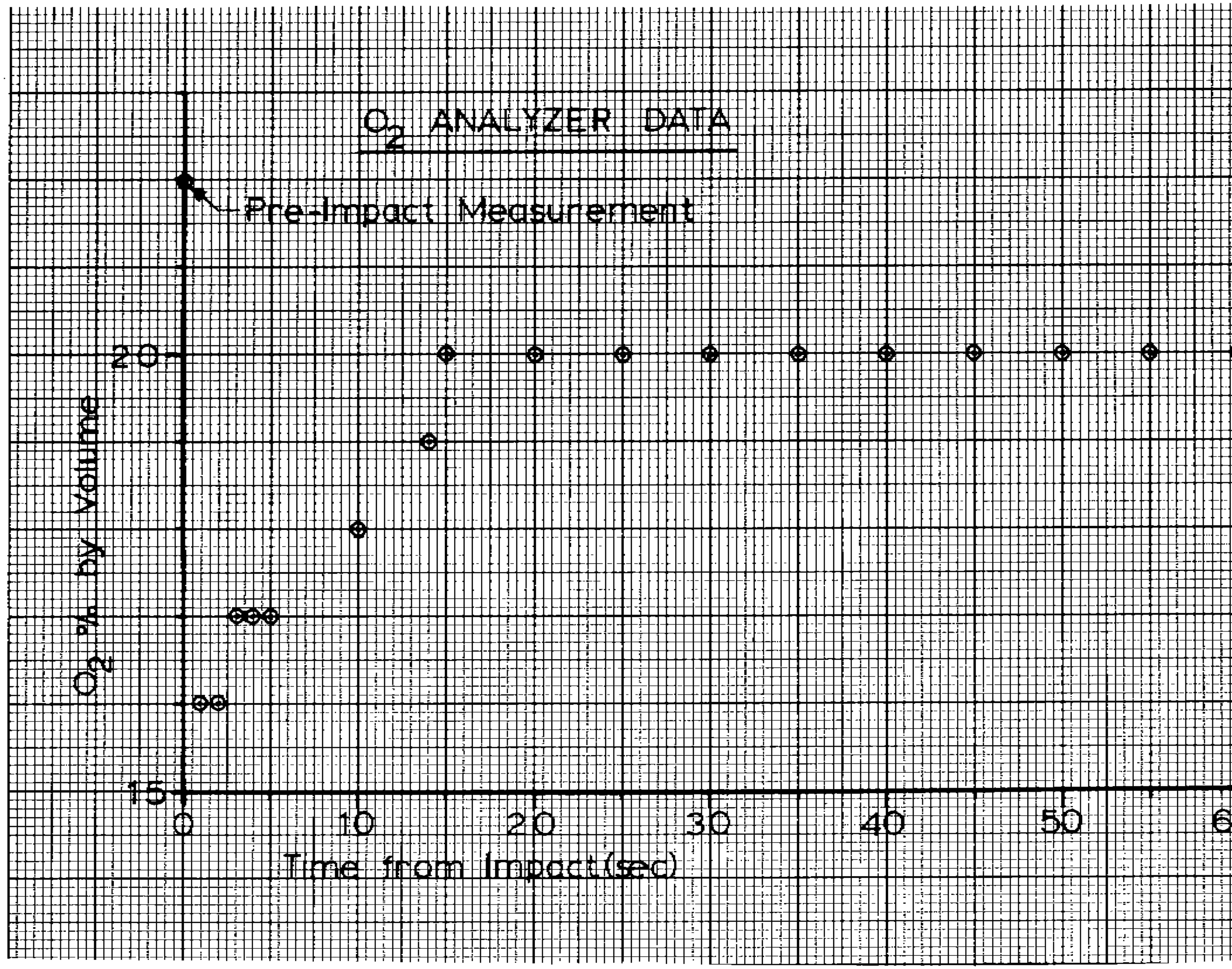


Figure 10. O_2 Analyzer Data

with the spark or 23mm API tests. The 23mm HEI projectile did produce significant combustion overpressures in the range of 650-700 kPa.

The results of the nitrogen tests were somewhat more as expected. However, some unexplainable results were obtained. Typical pressure histories for the 23mm HEI, API, and spark ignition sources are presented in composite form in Figure 11. The results presented in Figure 11 indicate that the HEI projectile produces a higher combustion overpressure in a shorter time than does the API or spark ignition source. There were no combustion reactions from the two tests involving high velocity multiple fragment impacts. The results of these tests were presented in Table 1.

4. HALON AND NITROGEN INERTING TEST RESULTS

All of the data for both inertants are presented in Table 1. The results of the Halon 1301 tests are graphically shown in Figure 12. The data presented in Figure 12 indicates that a completely inerted tank would require approximately 20% by volume of Halon 1301. A better understanding of what is actually happening in the TWS can be obtained by analyzing the composite time-histories shown in Figure 13. Note that as the Halon 1301 concentrations increased, the overpressure decreased gradually while the rise time increased dramatically. For Halon 1301 concentrations near 20%, the rise time was on the order of one full second.

The results of the nitrogen inerting tests are graphically shown in Figure 14. Note that the overpressure data is plotted against % by volume of O_2 for the nitrogen tests. The data presented in Figure 14 shows a gradual decline in overpressure as the % of O_2 decreases to approximately 14% by volume. At this point, the trend of the results was unexpected as the data dropped off sharply to no combustion reactions. There were several tests conducted around 14% by volume of O_2 in order to understand the reason for the sharp drop in overpressures at this concentration. It appeared that a threshold existed at the 14.0% by volume O_2 concentration. O_2 concentrations above 14.0% produced considerable combustion overpressures while O_2 concentrations below 14.0% produced no combustion overpressure. This data indicated that at N_2 inerting levels that result in O_2 concentrations below 14% by volume, the fuel tank is fully inerted against 23mm

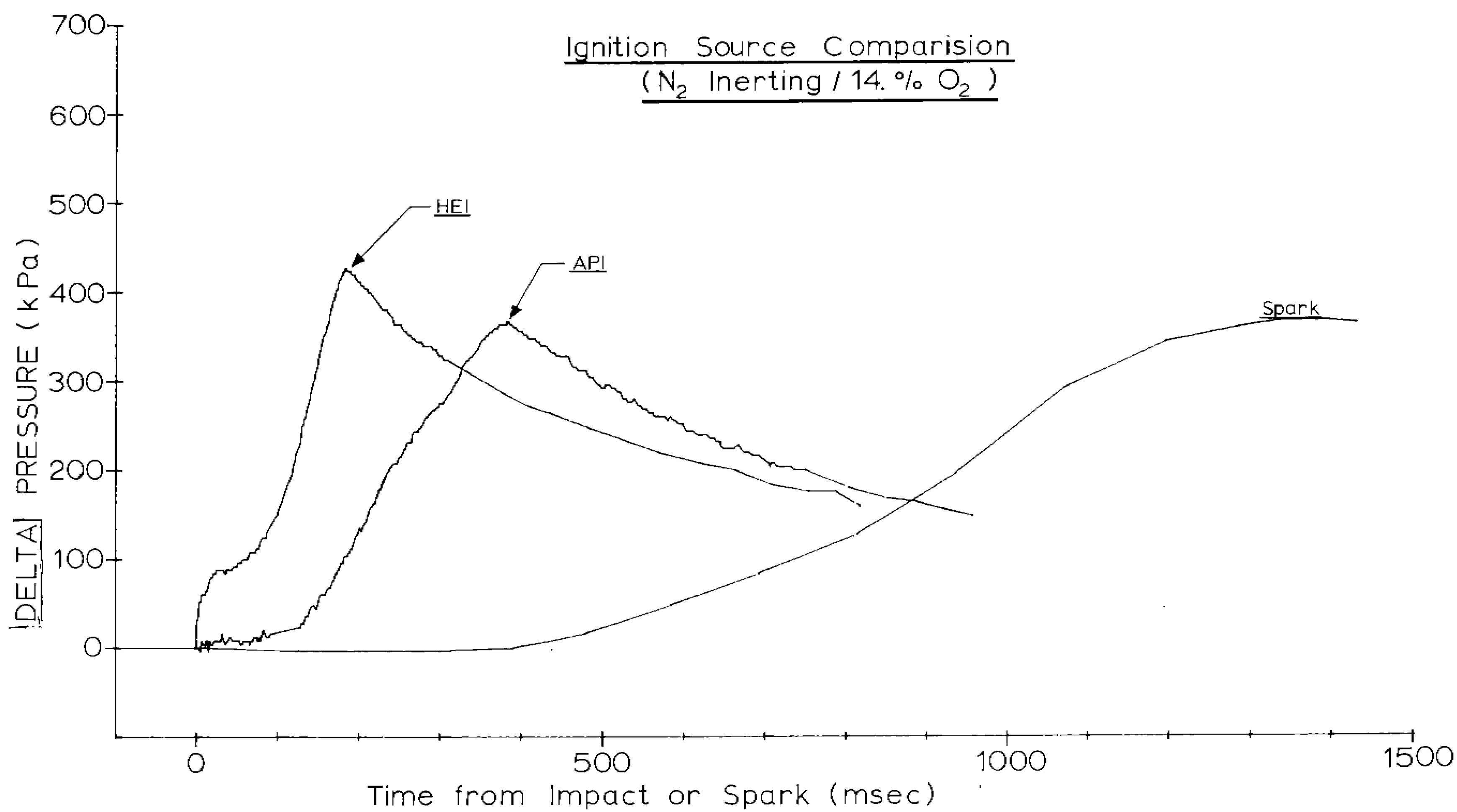


Figure 11. Ignition Source Comparison (N_2 Inerting/14. % O_2)

≈ 101 psi

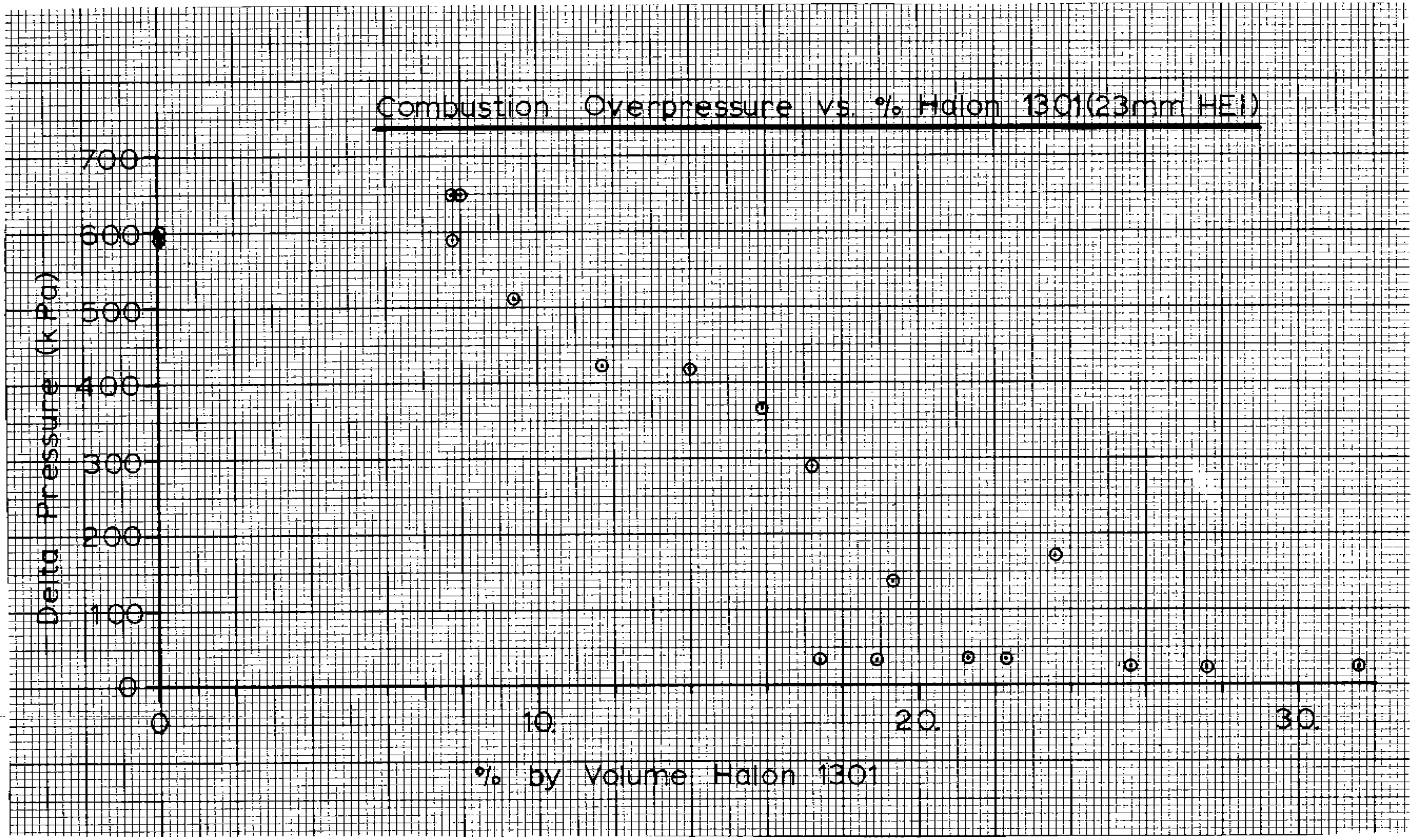


Figure 12. Combustion Overpressure vs % Halon 1301 (23MM HEI)

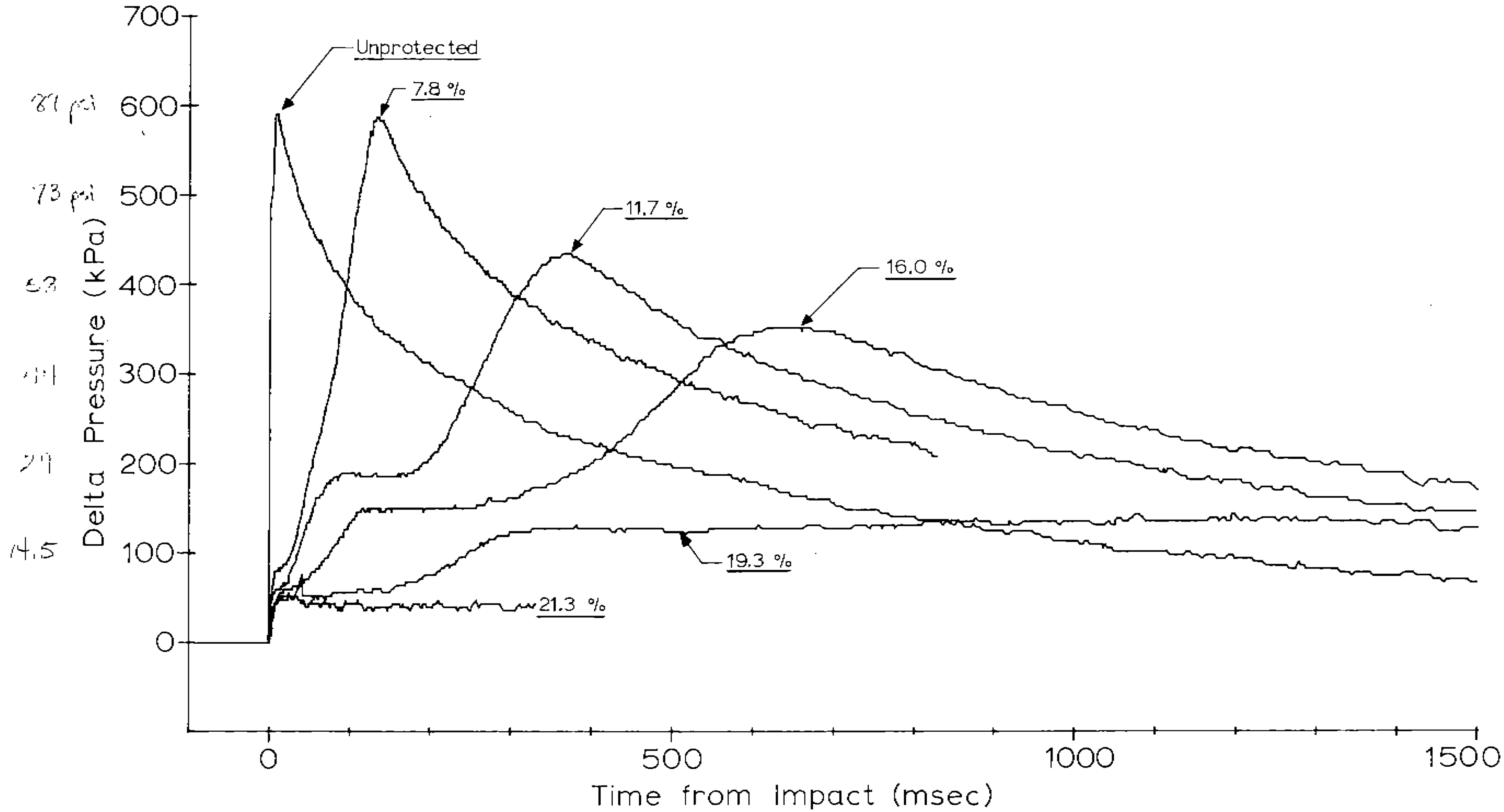


Figure 13. Overpressure Histories for Halon 1301 Inerting (23MM HEI)

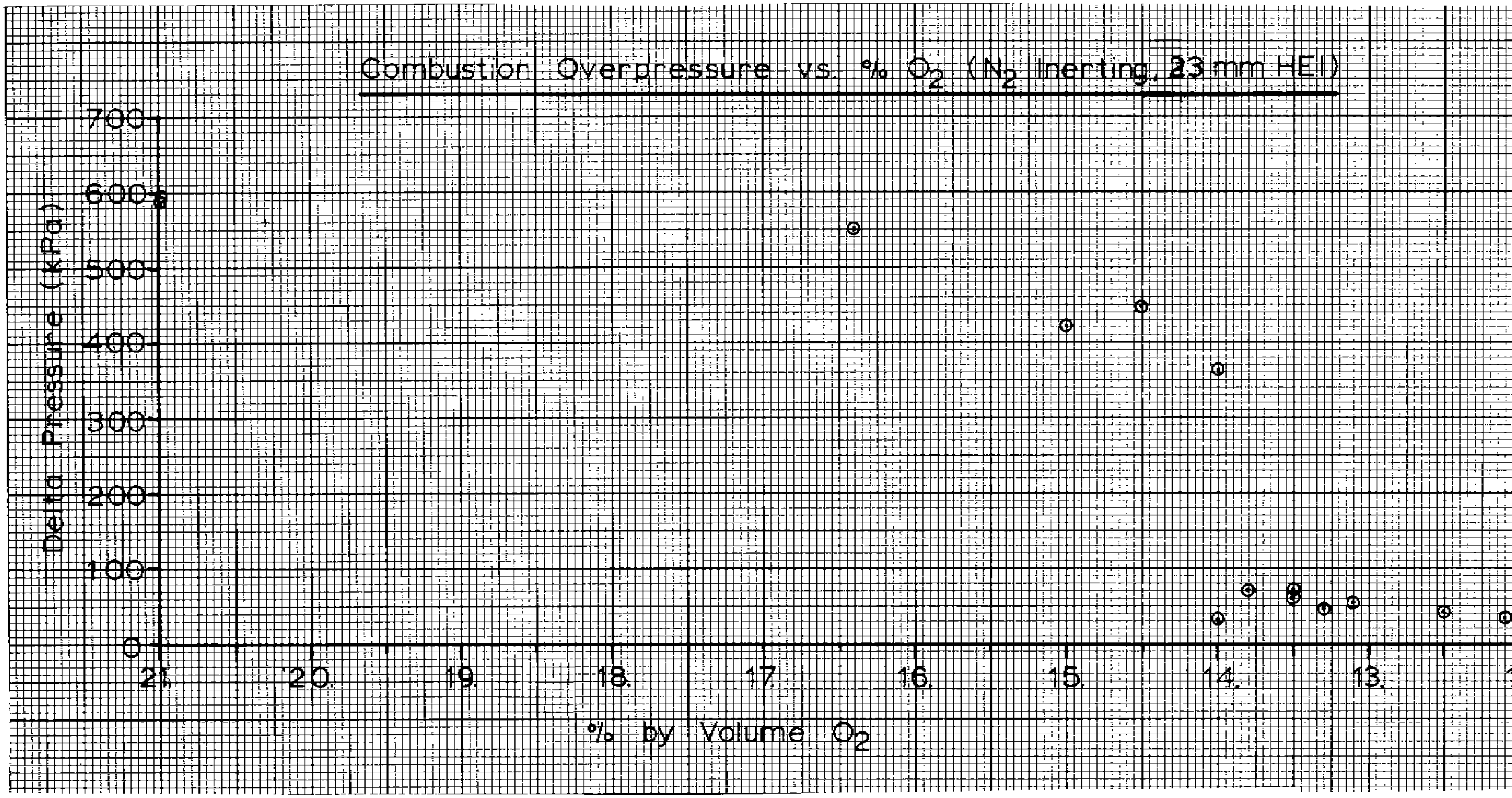


Figure 14. Combustion Overpressure vs % O_2 (N_2 Inerting, 23MM HEI)

HEI. The composite time histories for the various inerting levels are shown in Figure 15.

5. FOAM TEST RESULTS

Three tests were conducted in this test series with the TWS filled with red foam at a 22% voiding level. The foam was tested dry (i.e., without being wetted with fuel) and an optimum combustible mixture was obtained prior to the projectile impact. The test results are presented in Table 1 and a typical combustion overpressure history is presented in Figure 16. Figure 17 is a photograph of the foam installation after a 23mm HEI detonation. Notice the small pocket of foam destroyed in the immediate vicinity of the detonation. The foam also exhibited significant singeing on the surface of most voids indicating that combustion had taken place inside those voids. The highest combustion overpressure of any of the three tests in this series was 70 kPa which agrees with other data available on the red foam in reference 11.

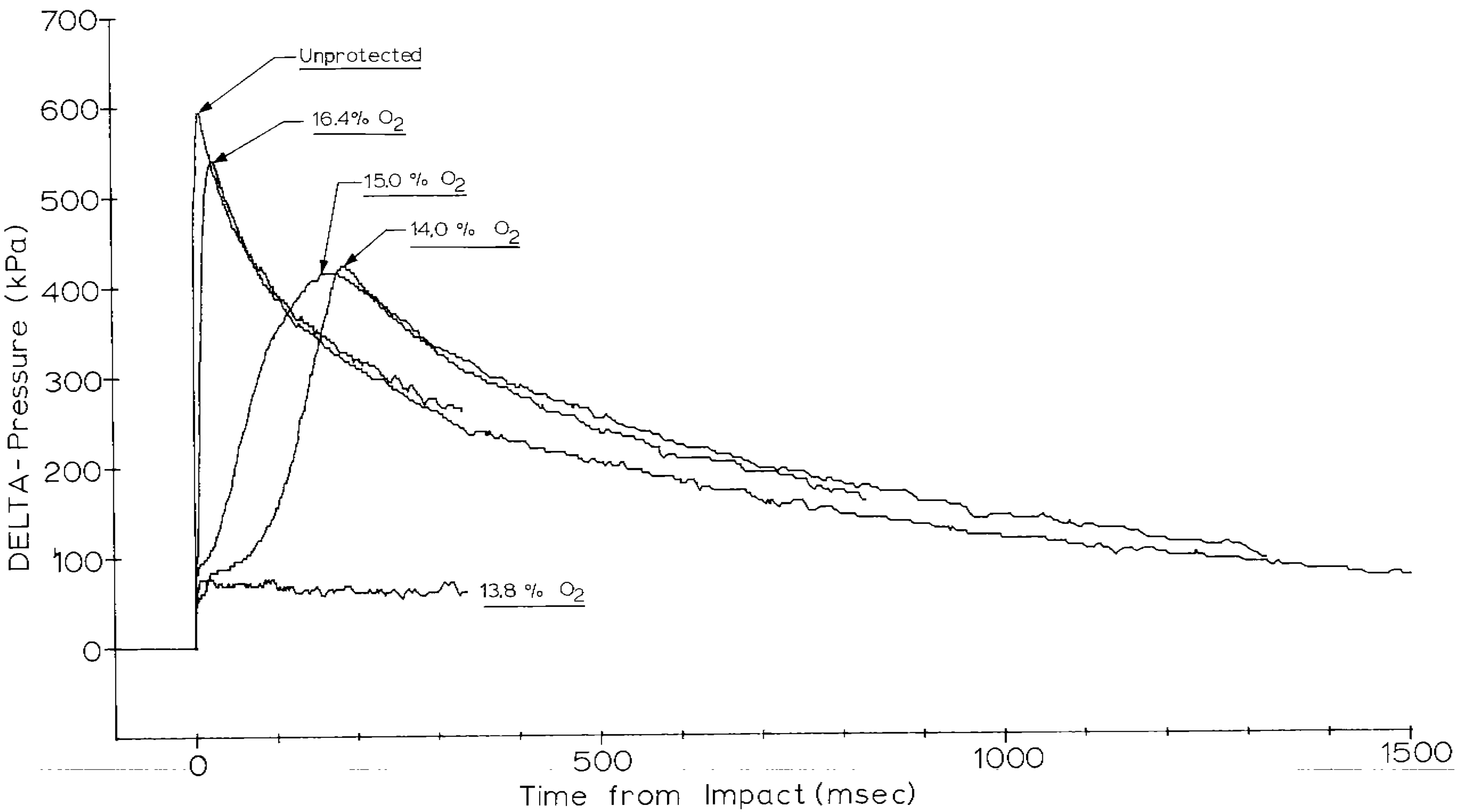


Figure 15. Overpressure Histories for N_2 Inerting (23MM HEI)

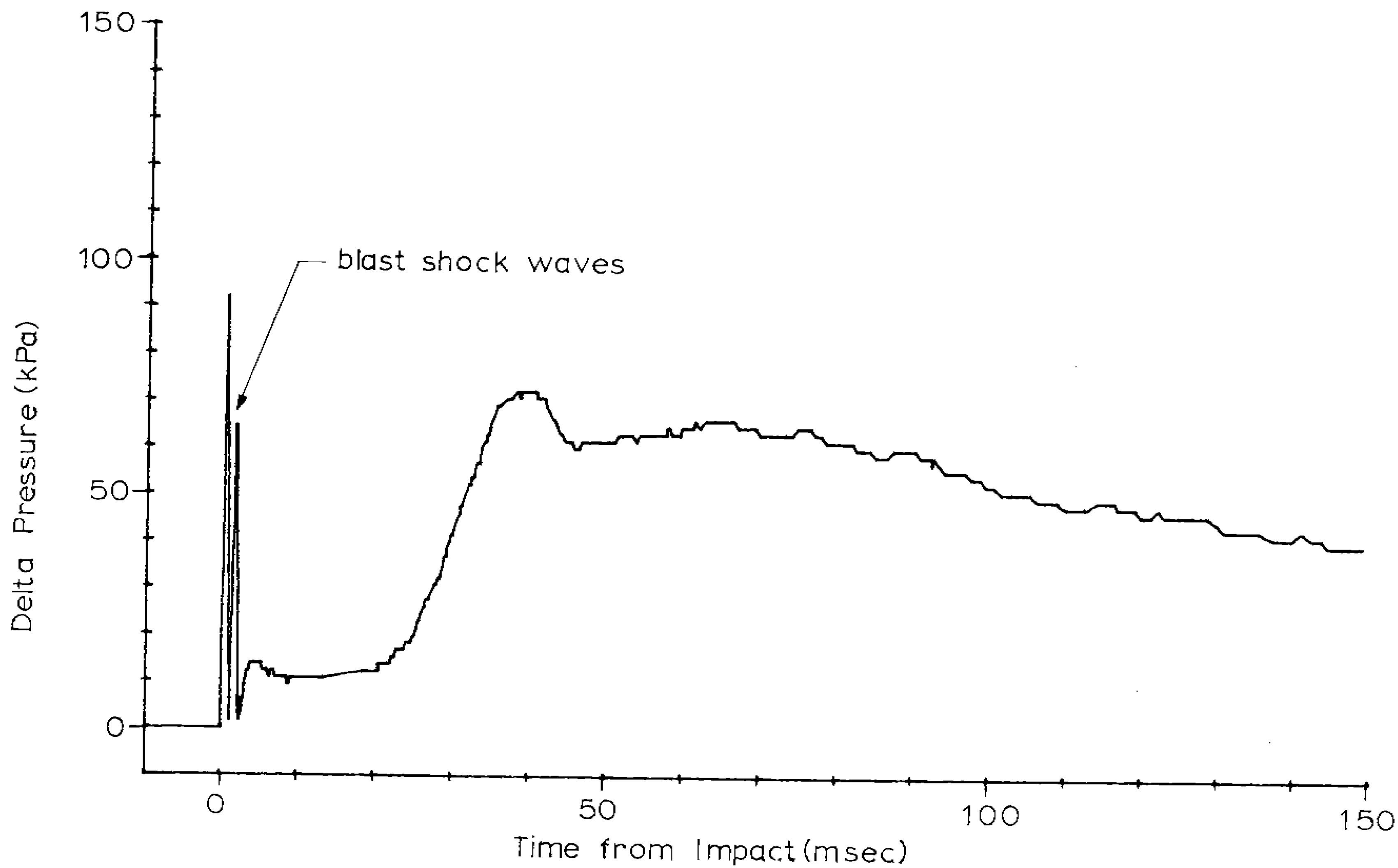


Figure 16. Combustion Overpressure History for Internal Foam at 22% Voiding (23MM HEI)

Figure 17. Foam Damage from 23MM HEI

TABLE NO. 1

INERTING TEST RESULTS

TEST NO.	THREAT	TYPE INERTING	% CF_3Br	% O_2	PEAK QUASI-STATIC ΔP (kPa)	RISE TIME (mSEC)	COMMENTS
47	Spark	Halon	8.0	---	0	NA	No reaction
61	23mm API	Halon	8.0	---	0	NA	No reaction
62	23mm API	Halon	7.8	---	0	NA	No reaction
51	23mm HEI	Halon	7.8	---	≃590	136	
58	23mm HEI	Halon	7.8	---	≃650	55	
60	23mm HEI	Halon	8.0	---	≃650	35	
74	23mm HEI	Halon	11.7	---	424	360	
75	23mm HEI	Halon	15.9	---	367	650	
76	23mm HEI	Halon	17.2	---	290	900	Initial Pres. = 105kPa abs.
77	23mm HEI	Halon	19.3	---	138	1000	Very flat pressure pulse
78	23mm HEI	Halon	23.6	---	172	1200	
79	23mm HEI	Halon	27.6	---	262	NA	No combustion pressure
80	23mm HEI	None	---	---	≃590	5	No inertant
81	23mm HEI	Halon	31.6	---	28	NA	No combustion pressure
82	23mm HEI	Halon	25.6	---	27	NA	No combustion pressure
83	23mm HEI	Halon	9.4	---	511	350	
84	23mm HEI	Halon	21.3	---	38	NA	No combustion pressure
85	23mm HEI	Halon	18.9	---	34	NA	No combustion pressure
86	23mm HEI	Halon	17.4	---	34	NA	No combustion pressure
88	23mm HEI	Halon	14.0	---	419	700	
90	23mm HEI	Halon	22.3	---	34	NA	No combustion pressure
91	23mm HEI	None	---	---	≃590	6	No inertant

TABLE NO. 1 (CONT.)

INERTING TEST RESULTS

TEST NO.	THREAT	TYPE INERTING	% CF_3Br	% O_2	PEAK QUASI-STATIC ΔP(kPa)	RISE TIME (mSEC)	COMMENTS
48	Spark	N_2	---	14.0	327	1900	
49	Spark	N_2	---	14.0	366	1840	
50	Spark	N_2	---	14.0	0	NA	No reaction
63	23mm API	N_2	---	14.0	372	390	
64	23mm API	N_2	---	14.1	0	NA	No reaction
65	23mm API	N_2	---	14.1	0	NA	No reaction
66	Frags	N_2	---	14.0	0	NA	No reaction
67	Frags	N_2	---	14.0	0	NA	No reaction
68	23mm HEI	N_2	---	14.0	34	NA	No combustion pressure
92	23mm HEI	N_2	---	12.1	34	NA	No combustion pressure
93	23mm HEI	N_2	---	16.4	552	22	
94	23mm HEI	N_2	---	13.3	48	NA	No combustion pressure
95	23mm HEI	N_2	---	13.1	55	NA	No combustion pressure
96	23mm HEI	N_2	---	14.0	363	500	
97	23mm HEI	N_2	---	13.5	63	NA	No combustion pressure
98	23mm HEI	N_2	---	13.5	63	NA	No combustion pressure
99	23mm HEI	N_2	---	15.0	422	170	
100	23mm HEI	N_2	---	14.5	448	115	
101	23mm HEI	N_2	---	13.8	72	NA	No combustion pressure
102	23mm HEI	N_2	---	12.5	41	NA	No combustion pressure
103	23mm HEI	Foam	---	---	38	NA	No combustion pressure
104	23mm HEI	Foam	---	---	11	NA	No combustion pressure
105	23mm HEI	Foam	---	---	76	38	

SECTION V

DISCUSSION OF RESULTS

It should be noted that the nitrogen inerting test results in Section IV indicated that O_2 concentrations below 14% by volume resulted in a total inerting of the TWS against the 23mm HEI projectile. Test results presented in references 1 and 3 using API projectiles and simulated warhead fragments indicated that total fuel tank inerting with nitrogen requires O_2 concentrations of 10% by volume or less. The data presented in Figure 14 shows a sharp reduction in overpressures at O_2 concentrations below 14% by volume. The data at concentrations above 14% by volume exhibited a negative slope, that if projected out, would have reached zero overpressure at approximately 9% by volume. It appears that the difference between HEI and API results is due to the sharp reduction in overpressures at 14% by volume as presented in this report. A possible explanation for this combustion threshold can be theorized from two facts. First, the results presented in Section IV indicated that the 23mm HEI detonation consumed approximately 2% of the O_2 in the TWS. Second, nitrogen inerting is an O_2 dilution protection concept that reduces O_2 concentrations to a point where fuel/oxygen combustion can no longer occur. Based on these two facts, the detonation of the 23mm HEI could be scavenging available O_2 in the TWS faster than the fuel/oxygen combustion can occur, effectively reducing the O_2 concentration to a point where combustion cannot occur.

The tests described in this report were all conducted using a 750 liter TWS. The effects of reducing the volume of the TWS were not investigated in this test program due to resource constraints. However, there are several factors which could affect the performance of Halon 1301 and nitrogen in smaller ullage volumes: (1) The percentage of O_2 scavenged by the 23mm HEI detonation should increase and possibly cause further self-inerting; (2) the HEI induced quasi-static pressure will increase; (3) the ignition source (HE detonation and incendiary material) will fill a smaller volume and subsequently be more intense; (4) venting through holes in the fuel tank will cause a faster decline in the overpressures with smaller volume tanks. Some of these factors would tend to reduce peak overpressures while other factors would tend to increase the overpressures. The data presented in this report was obtained with "near" worst case test conditions. The author believes that the only factor which could drive required inerting levels higher would be ullage volumes smaller than 750 liters. Individual test programs are recommended when applying the data in this report to fuel tankage significantly different in size, shape, materials, etc. These test programs are necessary in order to determine which fuel system factors are dominate and to determine in which direction the results are driven due to each factor. At this time, it is recommended that only conservative applications of the Halon 1301 inerting performance data be applied to specific systems of interest.

Due to the small amount of testing performed with high velocity fragments in this test program, there can be no firm conclusions drawn. To fully understand the effects of fragment quantities, materials, velocities, shapes, etc. was beyond the scope of this program.

SECTION VI

CONCLUSIONS

From the data obtained in this test program, the following conclusions are presented:

1. The Soviet 23mm HEI projectile is a more intense ignition source than API projectiles and spark ignition sources, thereby causing higher combustion overpressures. when venting is ignored

2. A concentration of 20% by volume of Halon 1301 (CF_3Br) provides total fuel tank inerting for a 750 liter ullage volume against spark ignition and other sources up to 23mm API and HEI projectiles.

3. The test data presented in this report indicates that a reduction of the oxygen concentration to 14% by volume, by diluting with nitrogen, provides total fuel tank inerting for a 750 liter ullage volume against 23mm HEI projectiles. However, as discussed in the DISCUSSION OF RESULTS section, other reliable data indicates that for API and fragment projectiles, a reduction in oxygen concentration to 10% by volume is required for total fuel tank inerting. Therefore, in order to ensure adequate explosion protection for the entire range of threats, it is recommended that a 10% by volume oxygen concentration be achieved.

REFERENCES

1. Allan J. Ferrenberg and Joel Blickenstaff, Fuel Tank Non-Nuclear Vulnerability Test Program, Air Force Aero Propulsion Laboratory, Technical Report AFAPL-TR-74-83, Feb 1975.

2. Allan J. Ferrenberg and Edwin E. Ott, Incendiary Gunfire Simulation Techniques for Fuel Tank Explosion Protection Testing, AF Aero Propulsion Laboratory, Technical Report AFAPL-TR-73-50, July 1973.

3. P. B. Steward and E. S. Starkmen, Inerting Conditions for Aircraft Fuel Tanks, WADC Technical Report Nr. 55-418, Sep 1955.

4. Edwin Ott and Robert A. Lillie, Influence of Fuel Slosh Upon the Effectiveness of Nitrogen Inerting For Aircraft Fuel Tanks, AF Aero Propulsion Laboratory, Technical Report AFAPL-TR-70-82, Feb 1971.

5. Joseph M. Kuchta, Ralph J. Cato, George H. Martindill, and Irving Spolan, Ignition and Fire Suppression in Aerospace Vehicles, U. S. Bureau of Mines, Technical Report AFAPL-TR-71-93, Dec 1971.

6. Ralph J. Cato, George H. Martindill, and Joseph M. Kuchta, Ignition and Fire Suppression in Aerospace Vehicles (Phase II), U.S. Bureau of Mines, Technical Report AFAPL-TR-72-96, Dec 1972.

7. Michael G. Zabetakis, Flammability Characteristics of Combustible Gases and Vapors, U.S. Bureau of Mines, Bulletin 627, 1965.

8. Investigation of Turbine Fuel Flammability Within Aircraft Tank, FAA-ADS-67-7.

9. Aviation Fuel Safety, Coordinating Research Council, CRC Project No. CA-37-67, June 1964.

10. A. J. Holten, AX Fuel Tank Vulnerability Evaluation Report, AF Flight Dynamics Laboratory, Technical Report AFFDL-TR-74-55, July 1974.

11. Charles L. Anderson, Ballistic Evaluation of Aircraft Explosion Suppression Materials, AF Flight Dynamics Laboratory, Technical Report AFFDL-TR-76-98, May 1976.

12. Dupont "FREON" FE 1301 Fire Extinguishing Agent, Dupont Report No. B-29A, 1966.

13. Allan Ferrenberg and George W. Gandee, Effects of Ignition Sources on Combustion Suppression Techniques, AF Aero Propulsion Laboratory, Paper Presented at Fire Suppression and Inhibition Symposium, Aug 1973.

14. Unpublished technical analysis received from Falcon Research and Development, Denver, Colorado, Oct 1976. Analysis discusses oxygen depletion by 23mm HEI detonation products and explosive overpressures in the ullage. The work was performed for the Air Force Aero Propulsion Laboratory under Contract No. F33615-74-C-2057.

☆U.S.Government Printing Office: 1978 — 757-080/725

Brunson 5/6/88

Air Force Report Charles Anderson -

Used a Zirconium Oxide Sensor - that was later questioned due to high temperatures of combustion in tank - though these temps may have affected sensor readings

Suggested using a Wet - chemistry - Beckman Analyzer

ANDERSON turn analyzer off just prior to impact and back on immediately after impact.

Aaron Fletcher - contact in Chem for O_2 Analyzer
Instrumental Chemical Analysis Branch X1627 - other [illegible]